Air Force Invention No. AFB00497

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On _____ 6 December 2002 _____

                    (DATE OF DEPOSIT)

_____ Thomas C. Stover _____ 22,531 _____

NAME OF APPLICANT, ASSIGNEE, OR REG. REP.

_____ 6 December 2002 ___

          SIGNATURE   DATE

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re CIP Application of   Group Art Unit: 2872
Geoff P. Andersen   Examiner: A. Chang
Application Serial No. 09/427,457
Filed: 16 October 1999
For: HOLOGRAPHIC IMAGE CORRECTOR

Honorable Commissioner for Patents
     Washington D.C. 20231

Sir:

DECLARATION UNDER 37 C.F.R. 1.132

I, Geoff P. Andersen of Colorado Springs, Colorado, declare and say that:

1. I am the sole inventor in the above-identified application, effectively filed on 16 April
1997.

2. That I have a PhD in Physics (Optics) and am an adjunct professor at the Air Force
Academy here in Colorado.

3. That I have conducted research and experiments in writing holograms with split laser
beams to correct for aberrations in lenses so as to correct for such lenses to receive accurate
images therethrough.

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4. That based on my 12 years of experience in this field and numerous experiments, I can state first-hand that once a hologram is written to correct for a distorted objective, one can illuminate an article at the focal point of such objective and have the reflected light travel back through the objective and corrective hologram to the viewer who receives a corrected or clear image of the article.

Further, I have written a Paper on the subject and attach a copy hereto as Exhibit A. Based on my above experience and credentials I can also say emphatically that the essentials of holographically corrected microscopes, per my invention, are clearly shown in the original drawings of the above application e.g. at Figures 4, 6, 12, & 14, which are recognized as such by those skilled in the art.

5. I can further state that a further feature of my corrected microscope is the ability of making small height measurements on various points of an article, as shown in Figure 15 of the above application, described on page 14 of the specification and as recited in claim 36. That is, one records the hologram, per Figure 11 and reconstructs it, as shown in Figure 15, by retaining the original reference beam on reconstruction.

6. The above contour plot is made possible by employing arrays of pinholes such as array 162, for writing a hologram 166, per Figure 13. The hologram, so written, is then employed as hologram 141 in the optical circuit of Figure 15.
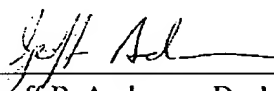
In my experience and based on numerous tests, the above hologram must be written through a pinhole array in order to subsequently obtain, per Figure 15, the fringes that represent a contour map of the height of points on an article. Such contour map cannot be realized by mounting a single pinhole on each branch of the split laser beam.

Also employing such pinhole array and writing holograms provide for a broader field of view in an image corrector such as a microscope, compared with writing similar holograms with a single pinhole in each branch of the laser beam.

7. I further declare that my statements herein, made of my own knowledge are true and that all statements made on information and belief are believed to be true; and furthermore that these statements were made with the knowledge that willful false statements and the like so made, are punishable by fine or imprisonment or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

_____6ᵗʰ December 2002_____
              Date

Geoff P. Andersen, Declarant

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Exhibit A ●

Holographically corrected microscope with a large working distance

Geoff Andersen and R. J. Knize

We present a design for a microscope with a simple objective lens with a high numerical aperture. The large amounts of aberrations present in the system are removed when a point-source image hologram is recorded. The resultant instrument has a large working distance (>0.17 m) and a moderate field of view over a limited bandwidth. We demonstrate the application of this device to imaging submicrometer details inside a vacuum.

OCIS codes: 090.0090, 180.0180, 110.3960, 220.1010.

1. Introduction

To resolve small details, high numerical aperture imaging optics are required. Fast objectives will have a large amount of spherical aberration, so the aperture is usually minimized, which means that the working distance must also be made very small. If a large working distance is required, expensive multielement combinations are necessary. An alternate solution is to use a single-element system and remove the aberrations holographically. We use holography to correct a simple lens with a large numerical aperture and achieve diffraction-limited imaging. The benefits of this design are the ability to observe objects in real time, at high magnification, in situations for which proximity to the sample is undesirable or otherwise impossible, such as samples under vacuum, in toxic or radioactive environments or in microbiological applications.

Holography was originally developed as a means for correcting the spherical aberration present in electron microscopy and has since been applied to many optical systems, including microscopes.[1-12] Two distinct types of holographic microscopy have been investigated previously. The first[5,6] involves recording holograms of objects by use of good quality microscopes and observing the images in a separate step, with the hologram doing little to correct for aberrations present in the system. In the second design type,[7,10] a hologram of the object is recorded by

use of a microscope of any optical quality, with the aberrations removed when a phase-conjugate reconstruction is used. However, this method still requires a good quality microscope to observe the reconstructed images, and as with the other designs, a new hologram must be recorded for each object. In our microscope design, the system aberrations for imaging a point source of light are recorded holographically. This hologram can then be used to remove the same aberrations present with any object imaged by the optical system.

The basic operation of a holographically corrected refracting microscope is shown in Fig. 1. The recording procedure begins with a spatial filter that illuminates a simple objective lens [Fig. 1(a)]. Although the size of the pinhole in the spatial filter does not affect the final resolution of the microscope, it should be sufficiently small that the objective is evenly illuminated. The light is focused by the objective and gathered by an imaging lens that collimates the light and images the objective lens onto the plane of the hologram. One can increase the field of view with this imaging condition, when an aberrated objective is used, by defining a particular phase shift associated with each point on the lens for any field point.[13] The recording media (in our case plate film) is aligned perpendicular to the object beam, and the hologram is recorded with a diffraction-limited plane wave.

The processed hologram is returned to the original recording position for reconstruction [Fig. 1(b)]. With the spatial filter illuminating the objective once more, the light passes through the optical system, reconstructing the plane-wave reference beam. If the spatial filter is replaced with an object illuminated with light of the recording wavelength, light from a

The authors are with the Department of Physics, Laser and Optics Research Center, Suite 2A6, 2354 Fairchild Drive. U.S. Air Force Academy, Colorado Springs, Colorado 80840.
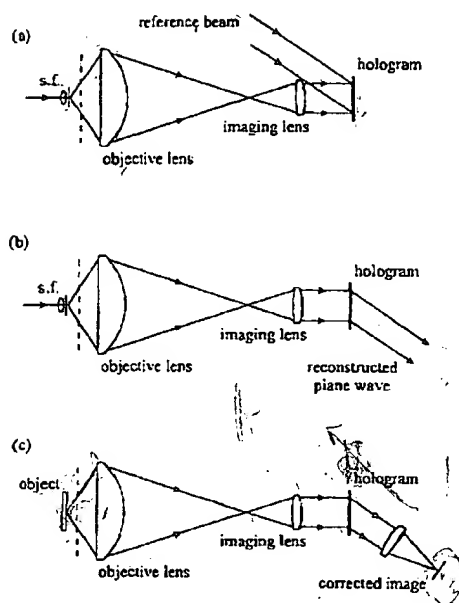
Exhibit A

Fig. 1. (a) Recording. Laser light is spatially filtered (s.f.) to illuminate the objective lens that is then imaged onto the film. A hologram is recorded with a plane-wave reference beam. The dashed line indicates the possible inclusion of a vacuum window. (b) Reconstruction. With the setup unchanged, the object beam reconstructs the original reference beam. (c) Imaging. Light from an object placed at the pinhole position reconstructs the reference beam that can be focused to form an unaberrated image.

point corresponding to the original position of the pinhole will reconstruct the reference beam with the object information retained [Fig. 1(c)]. If this beam is focused, an unaberrated image of the source point will be obtained. To an extent, the aberrations of nearby points will be similar to that of the source point, so the hologram can correct for a finite field of view.

2. Experimental Evaluation

An experiment was conducted with an inexpensive Pyrex plano–convex objective lens (f = 165 mm, D = 108 mm) illuminated by a spatial filter, consisting of a 60× microscope objective and a 0.5-μm pinhole, at a working distance of 175 mm. For a more dramatic demonstration, the spatial filter was placed inside a vacuum chamber, illuminating the objective through a thick glass window (indicated by the dashed line in Fig. 1). In this configuration, the focused beam has a paraxial spot size 240 mm in diameter and over 1900 waves of spherical aberration, along with several waves due to the poor surface quality of the lens and window. A diffraction-limited imaging lens (f = 100 mm, D = 36 mm) was placed at the circle of least confusion to form a 25-mm-diameter image at the plane of the film, 110 mm away. The intensity distribution across the image beam drastically changes either side of the image plane, so to ensure an even intensity (for the most efficient hologram), the plate is placed perpendicular to the object beam. A hologram was recorded with a diffraction-limited refer-

ence beam incident on the plate from an angle of approximately 30°. Having the reference beam come in from an angle results in a diffracted beam, on reconstruction, with an elliptical profile. This does not result in any aberration being present in the final beam; however, it does result in a change in aspect ratio, which can be corrected digitally. The plate film was held in kinematic holder that made it possible to replace the hologram to its original position after processing. For this experiment we used a cw, frequency-doubled Nd:YAG (λ = 532-nm) laser and a bleached Agfa 8E56 plate film to record phase transmission holograms with typical diffraction efficiencies (ratio of first diffracted order power to input power) of 70–90%.

After exposure and processing, the hologram was returned to the holder, and the chamber containing the spatial filter was evacuated to 10^{-4} Torr. With the setup essentially unchanged, the spatial filter illuminated the objective lens forming the original object beam that reconstructed the reference beam at the hologram. We tested the fidelity of the reconstructed beam by examining the focal spot [Fig. 2(a)], and by forming an interference pattern against the original reference beam [Fig. 2(b)]. From these results we can conclude that the on-axis correction was better than $\lambda/10$.

The spatial filter was replaced with a sinusoidal amplitude grating (with a grating spacing of 0.885 μm) illuminated from the rear by laser light passing through a rotating diffuser to remove speckle. The chamber was then evacuated once more, with the light from the object reconstructing a diffracted beam that was focused to form an image of the grating [Fig. 2(c)]. The low visibility of the fringes is a result of the operation near the Rayleigh limit of the microscope.

For a reflecting object, a slightly different setup was needed to illuminate the object. We recorded a new hologram with a half-silvered plane mirror placed just before the imaging lens and at a 45° angle to the incoming beam. This made it possible, on reconstruction, to introduce a beam that travels backward through the system to provide on-axis illumination to a reflecting sample. Figure 2(d) shows an image of an integrated circuit (under vacuum) with details of <3 μm clearly visible. The resolution of such fine details under vacuum and at a working distance of >170 mm should have many benefits. One area that benefits, in particular, is the microchip industry; this microscope makes it possible to view such processes as plasma deposition or etching of microscopic features in situ.

These measurements show that even with such large initial errors, diffraction-limited, on-axis correction and imaging is possible. However, since no off-axis aberrations are recorded, there is a reduction in correction with field angle. The field of view and the depth of focus were determined when the position of the spatial filter (no longer under vacuum) was translated and the diffracted beam was reexamined interferometrically. We found the diffraction-limited field of view to be ±10 μm with a ±2-μm depth of
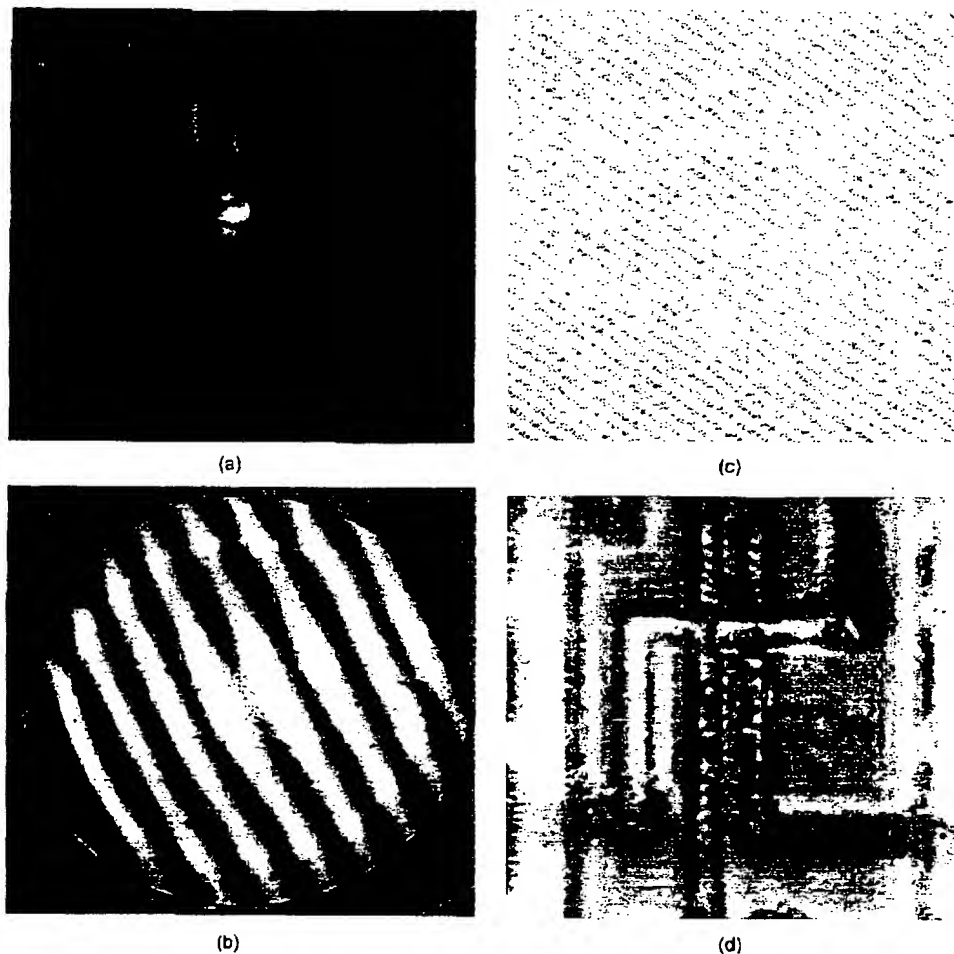
Exhibit A ●

Fig. 2.   (a) Focal spot of the reconstructed beam.   (b) Interference pattern of the reconstructed beam against a plane wave showing $<\lambda/10$ wave-front error.   (c) Image of a sinusoidal grating (1130 lines/mm) in transmission.   (d) Image of a microcircuit in reflection.   The tracks are approximately 3 μm wide.

focus.   The effect of these uncorrected off-axis aberrations is apparent in the large-field images shown in Figs. 3(a) and 3(b).   Although the field of view is small, by scanning a sample under the on-axis recording point, one can view a large object at the highest possible resolution.   This technique is commonly used in confocal and electron microscopy to increase the effective field of view.

In addition to a narrow field of view, this microscope also has a small operating bandwidth.   The hologram records the phase error of the system at a particular wavelength, and as such, there will be a wavelength-dependent error.   The final, corrected phase error ϕ_2 is related to the initial phase error ϕ_1 and the read–write wavelengths (λ_2 and λ_1 respectively) by

$$\phi_2 = \frac{|\lambda_2 - \lambda_1|}{\lambda_2} \phi_1. \tag{1}$$

A reconstruction of the point source was performed with Argon–ion (λ = 514 nm) and green He–Ne (λ =
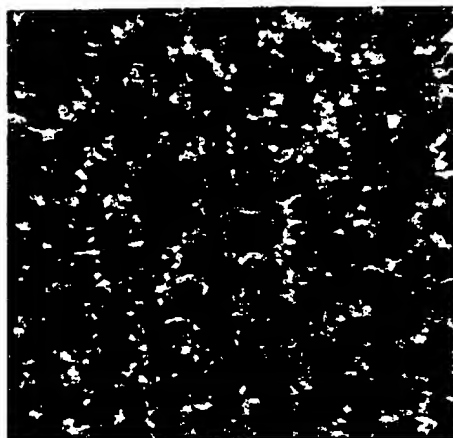
543.5 nm) lasers.   The residual aberration at these wavelengths was found to be 68 and 41 waves, which is in good agreement with this simple theory.   Given the large initial wave-front error in this system, perfect imaging can occur only at the recording wavelength.   However, the bandwidth could be increased, quite simply, if the objective lens characteristics were optimized to reduce the amount of spherical aberration initially present in the system.

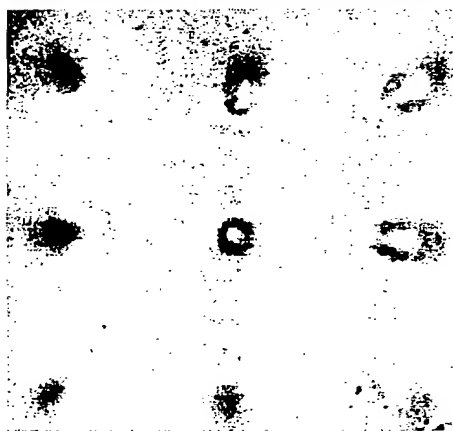## 3.   Alternative Designs or Modes of Operation

Although we have demonstrated the correction of a microscope with a simple refracting objective, several other designs are possible.   First, a Fresnel lens or Fresnel–Gabor zone plate could serve as the objective element.   The microscope setup is the same as used for a conventional lens; however, with this design, much larger numerical apertures are possible and the overall weight of the instrument is decreased.

A second possible design could incorporate a reflecting, conic objective, used in an off-axis arrange-
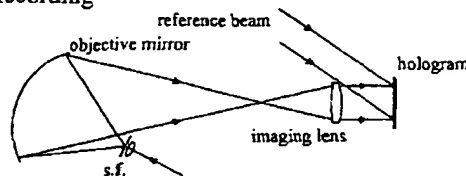
Exhibit A

(a)

(b)

Fig. 3.   Images showing the effect of uncorrected off-axis aberrations over a large field of view: (a) blood cells, (b) array of 5-μm holes.
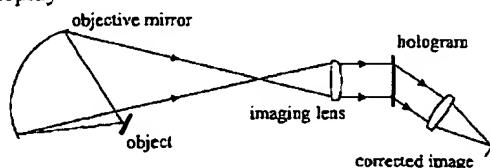
Recording

Replay

Fig. 4.   Reflecting microscope.   The recording and the replay setups are shown for a holographically corrected microscope with an off-axis objective element.

4.   Conclusion

We have investigated the design of a holographically corrected refracting microscope with a simple objective with a high numerical aperture operating at a large working distance.   A point source of light is used to record an image hologram of the objective, which makes it possible to correct for the aberrations present when viewing any object.   The simple, inexpensive device provides a useful field of view over a limited bandwidth while making it possible to view objects in situations in which traditional microscopes fail.   The microscope can be used as an inexpensive method of high-resolution image reduction and microlithography and can be adapted to incorporate conic reflectors, zone plates, or Fresnel lenses as the objective elements.

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ment as shown in Fig. 4.   In this arrangement there will be large amounts of off-axis aberrations present in the system.   However, these wave-front errors will be recorded and corrected holographically, just as with the on-axis aberrations in the refracting microscope.   The advantage of using a reflecting objective is that the microscope operation can be extended into UV wavelengths for greater resolution.

We have demonstrated how this microscope can be used for producing magnified images of objects, although it is possible to use the same instrument for photoreduction and micromachining.   If a phase conjugate of the original reference beam is incident on the hologram, a phase conjugate of the object beam will be reconstructed, making it possible to create high numerical aperture, diffraction-limited focal spots.   Using low-power pulsed lasers, we have used this technique to machine pinholes less than 1 μm into metal foils under vacuum. Furthermore, images can be projected through the system for high-resolution photolithography or photoreduction.

Exhibit A

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